Reflected Solar Science and Instruments

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RSS Level 1 Requirements

- Solar spectral nadir reflectance of the Earth and its atmosphere relative to the solar irradiance spectrum with
  - Absolute uncertainty ≤0.3% relative to global mean reflected solar energy (k=2)
  - Sampling to provide global coverage and degrade climate trend accuracy by less than 20%
- CLARREO shall enable inter-calibration with climate relevant operational sensors

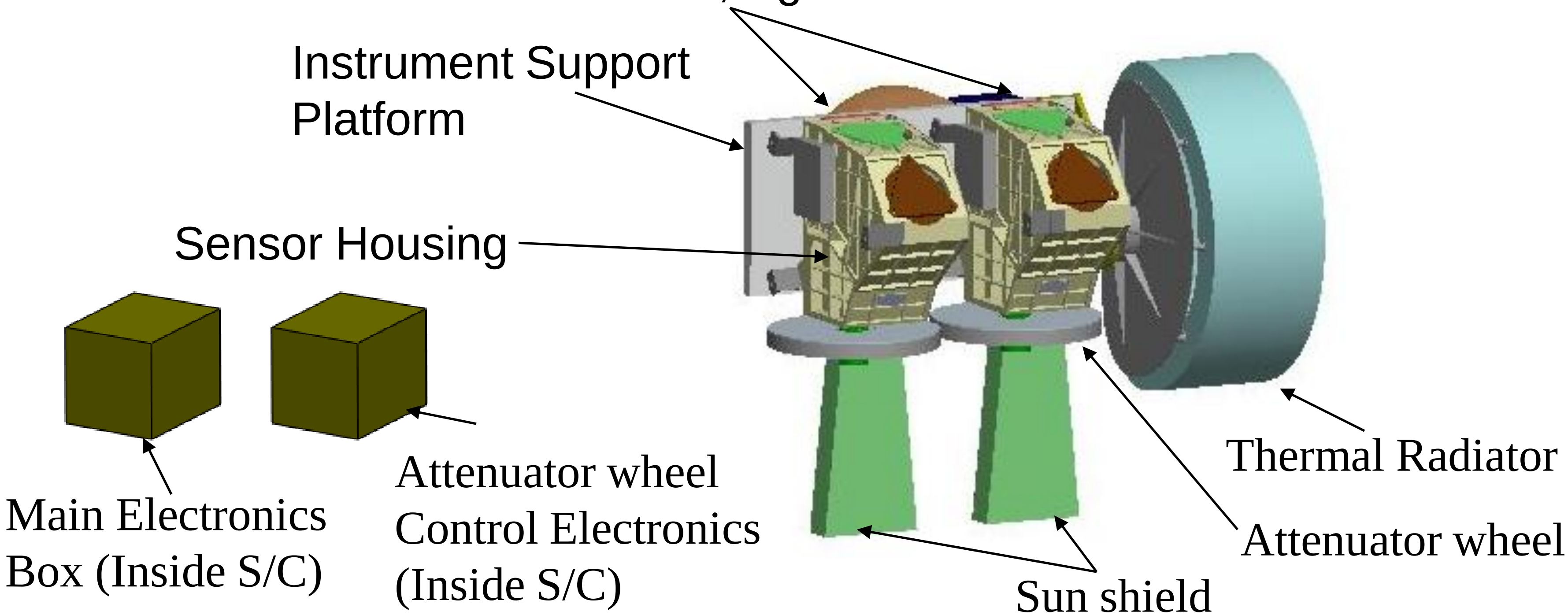
RSS Level 2 Requirements

- Spectral range of 320 – 2300 at better than 4-nm sampling and 8-nm resolution
- Spatial sampling interval at nadir from 600 km orbit of 0.5 km with resolution of 0.5 km and swath width >100 km
- SNR values for a single sample at radiance based on a reflectance of 0.3 and incident solar zenith angle of 75 degrees:
  - SNR> 20 for wavelengths 320 – 380 nm
  - SNR> 33 for wavelengths 380 – 900 nm
  - SNR> 20 for wavelengths 900 – 2300 nm
- Polarization sensitivity for 100% polarized input that is <0.50% below 1000 nm and <0.75% at other wavelengths
- Radiometric calibration accuracy of 0.3% reflectance integrated across all wavelengths and within individual bands

RSS Instrument Concept Design

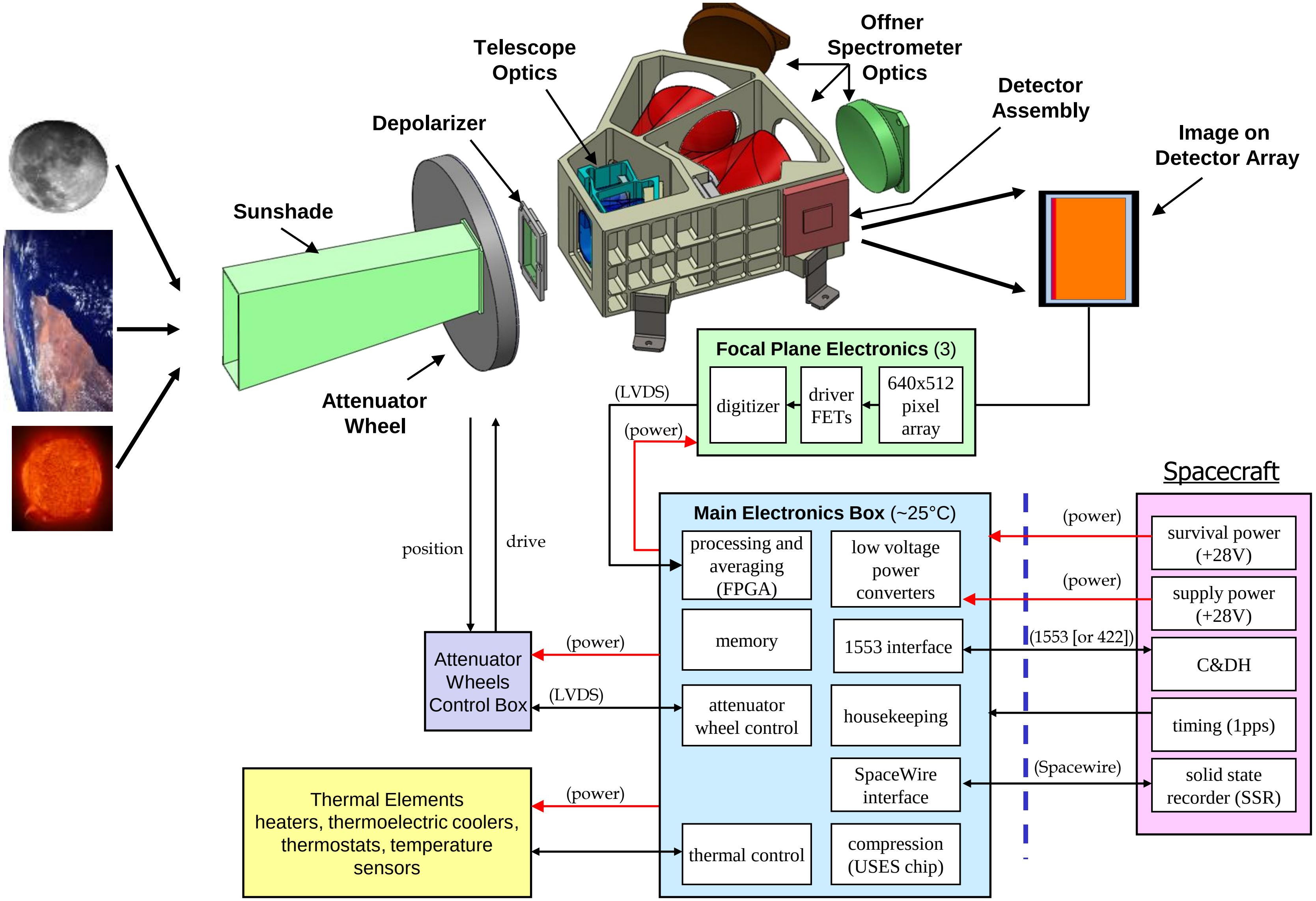
2x Optical Packages

- Blue Channel 320-640nm, silicon detectors
- Red/NIR Channel 600-2300nm, HgCdTe detectors



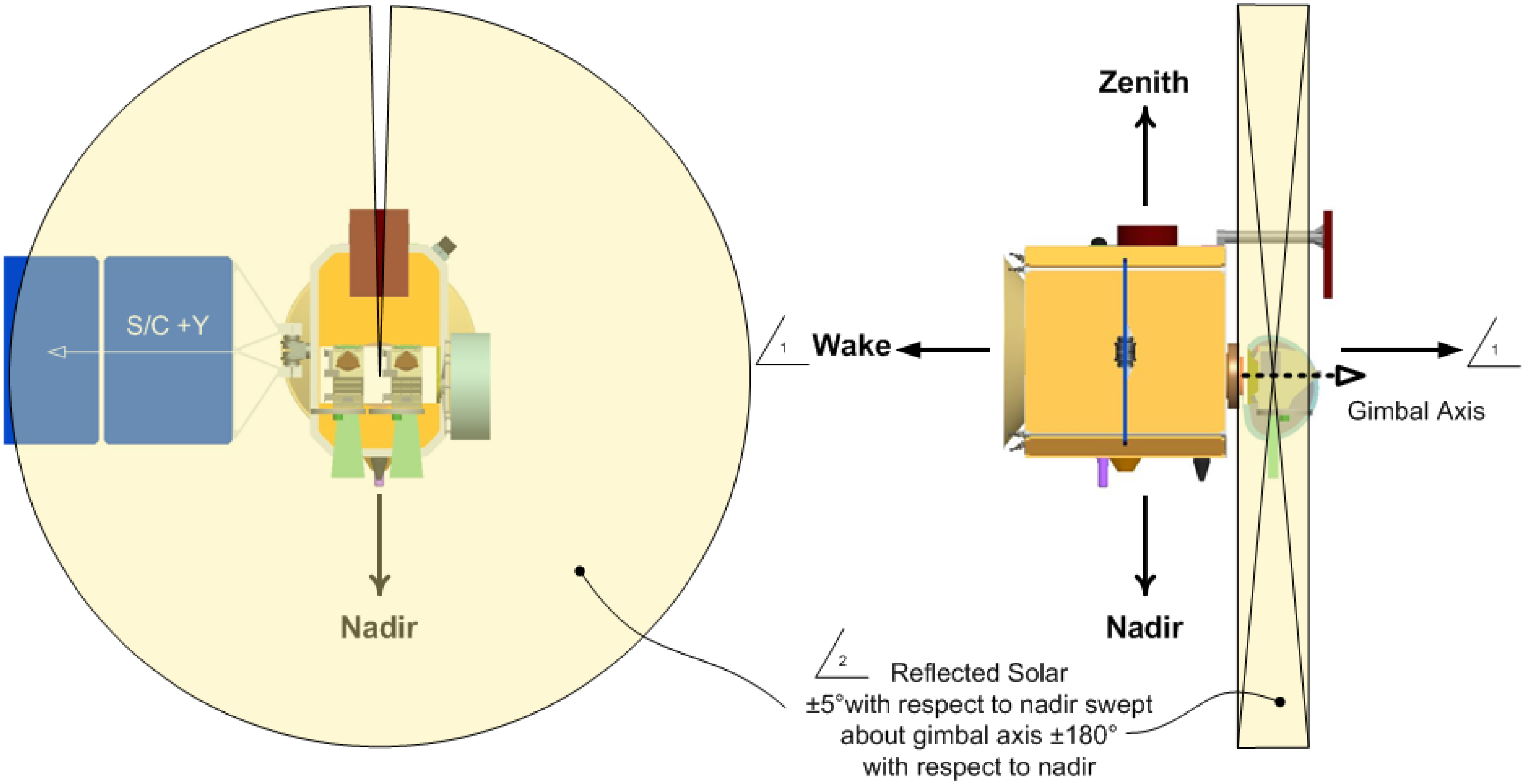
- Commonality of design of two boxes aids in calibration
- All-aluminum materials including telescope optics with Offner design
- Cooled focal planes tailored for each spectral region
  - 250 K for Silicon
  - 200 K for HgCdTe

RS Block diagram



Reflected Solar Suite Accommodations

Mass	Avg. Power	Peak Power	Data Rate	Data Volume
70 kg	96 W	117 W	0.5 Mb/sec	66 Gb/day

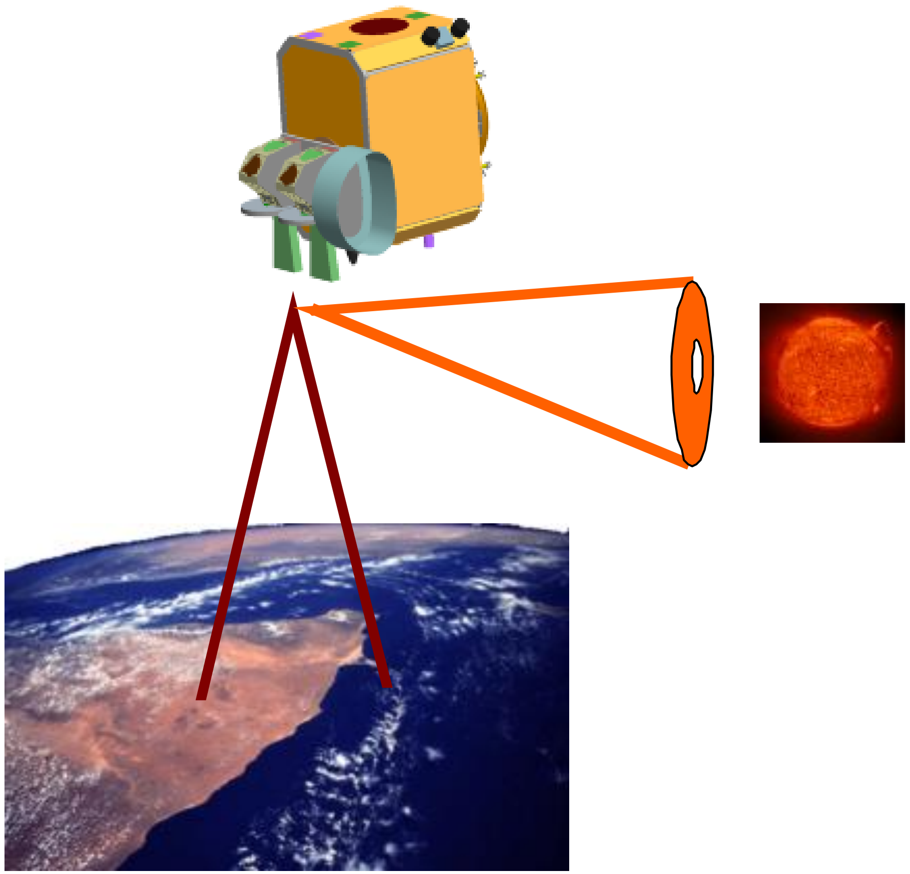


Reflected Solar Suite Fields-of-View

Reflectance Retrieval

- Reflectance retrieval is ratio of earth-view data to solar-view data
- Solar view calibrates each detector
  - Response of i[th] detector is

$$R_{i,\lambda}^{sensor} = \frac{\sum_{x_{solar}} \sum_{y_{solar}} S_{i,\lambda}^{solar}(x'_{solar}, y'_{solar})}{(T_{attenuator} A_{attenuator}) E_{solar}}$$



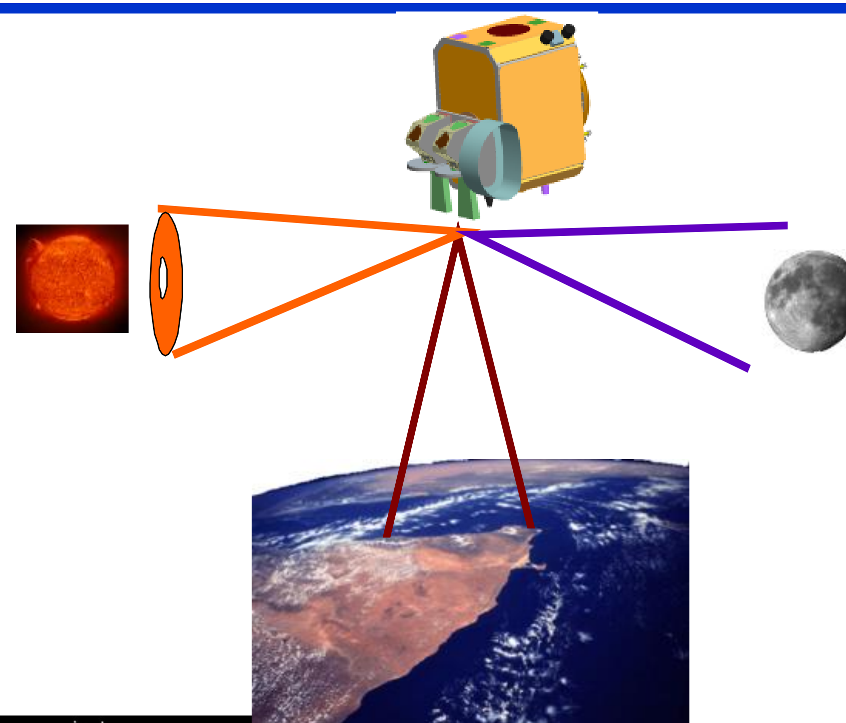
- Bidirectional reflectance distribution function (BRDF) is

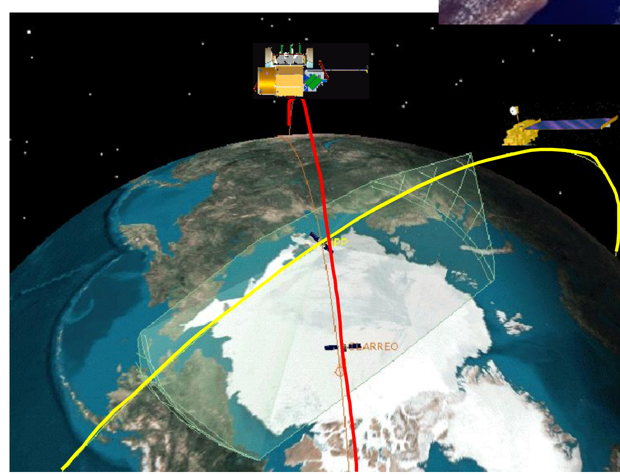
$$BRDF_{i,\lambda}^{earth} = \frac{L_{i,\lambda}^{earth}}{E_{sun} \cos\theta_{solar}} = \frac{S_{i,\lambda}^{earth}}{R_{i,\lambda}^{sensor} A_{sensor} \Omega_{sensor}} \frac{(T_{attenuator} A_{attenuator}) R_{i,\lambda}^{sensor}}{\cos\theta_{solar} \sum_{x_{solar}} \sum_{y_{solar}} S_{i,\lambda}^{solar}(x'_{solar}, y'_{solar})}$$

Level 1 Science requirement is stated in terms of a reflectance retrieval

Operating Modes

- Reflectance retrieval, calibration and inter-calibration requirements lead to three basic operating modes
  - Nadir Data Collection (>90% data collection time)
  - Solar Calibration
  - Inter-calibration of other on-orbit assets
- Verification of calibration drives the need for lunar views



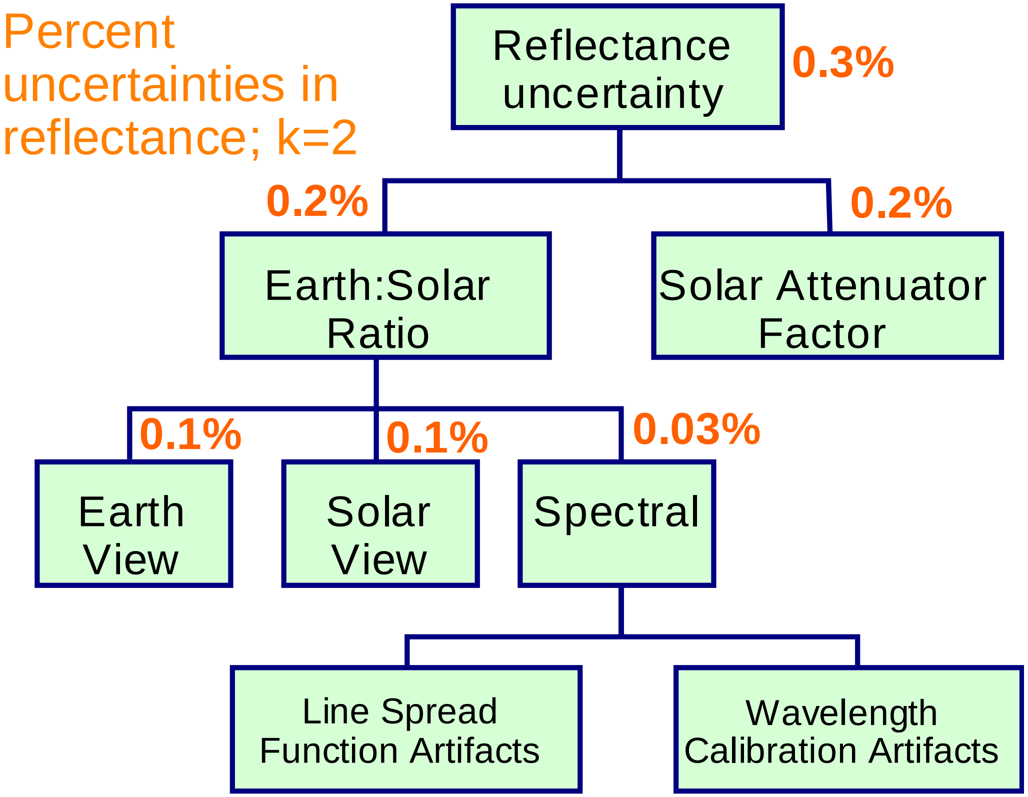


Three basic operating modes for RSS instrument

Error Budget

- Radiometric calibration requirement of RSS instrument is and order of magnitude stricter than past sensors
- Reflectance obtained by ratio of earth view to a solar view
- Error budget based on current state of the art
  - NIST methods
  - Recent earth science missions (SORCE, SeaWiFS, MODIS)

Dominant error sources identified as stray light and attenuator characterization

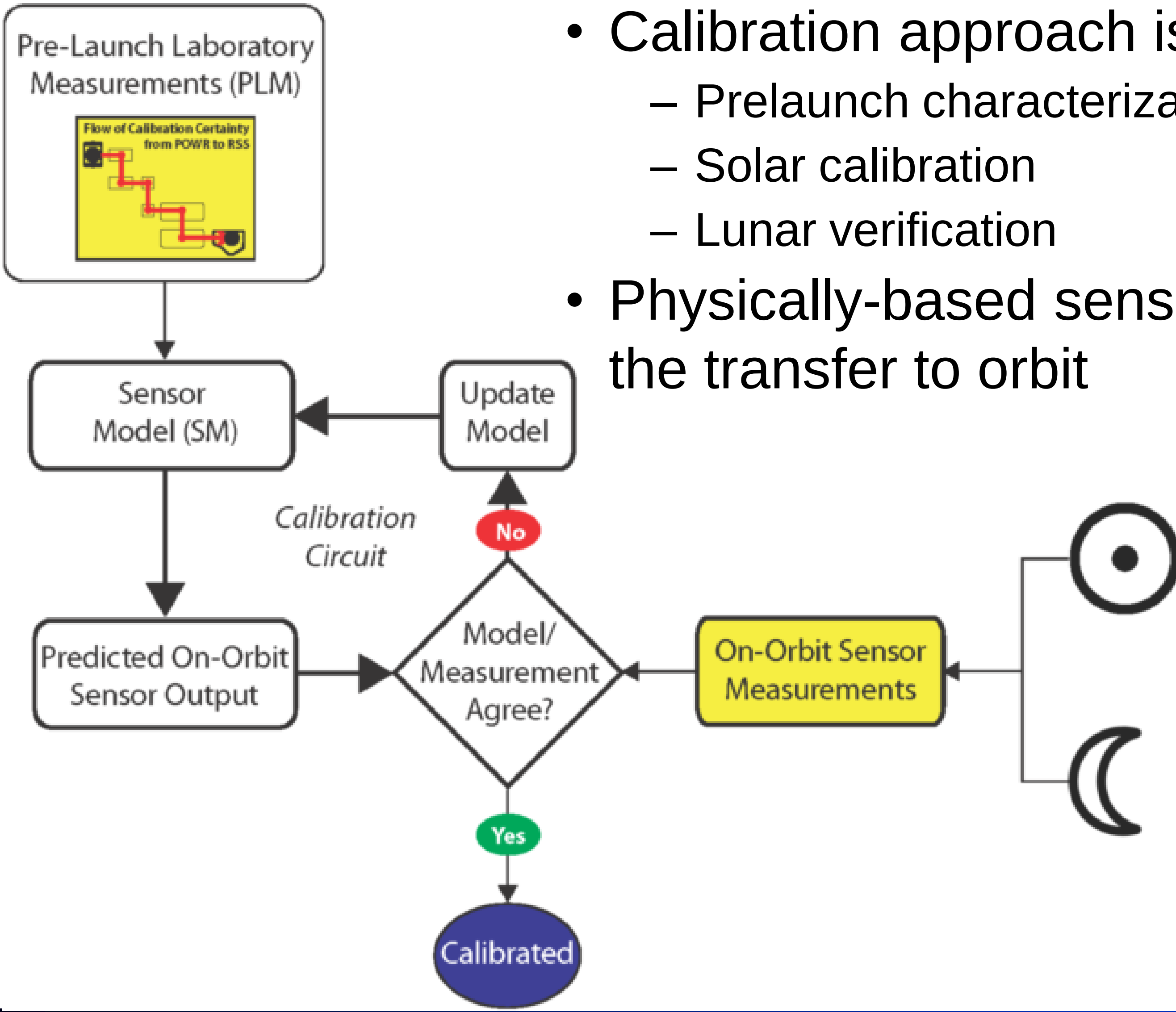


$$BRDF_{i,j}^{earth} = \frac{\left\langle R^{sensor} \right\rangle S_{i,j}^{earth}}{R_{i,j}^{sensor} \sum_{i} \sum_{j} S_{i,j}^{solar} r_{i,j}^{flat\ field}} \frac{T_{attenuator} A_{attenuator}}{A_{sensor} \Omega_{sensor}} \frac{a_{sensor}^{straylight} \omega_{sensor}^{straylight} a_{attenuator}^{straylight}}{r_{i,j}^{flat\ field} r_{i,j}^{nonlinearity} r_{i,j}^{polarization}}$$

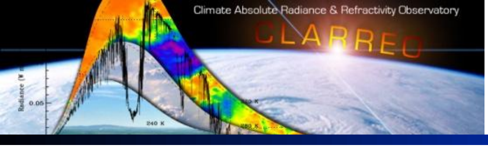
See backup charts for definition of terms

Dominant error sources are known

Calibration approach

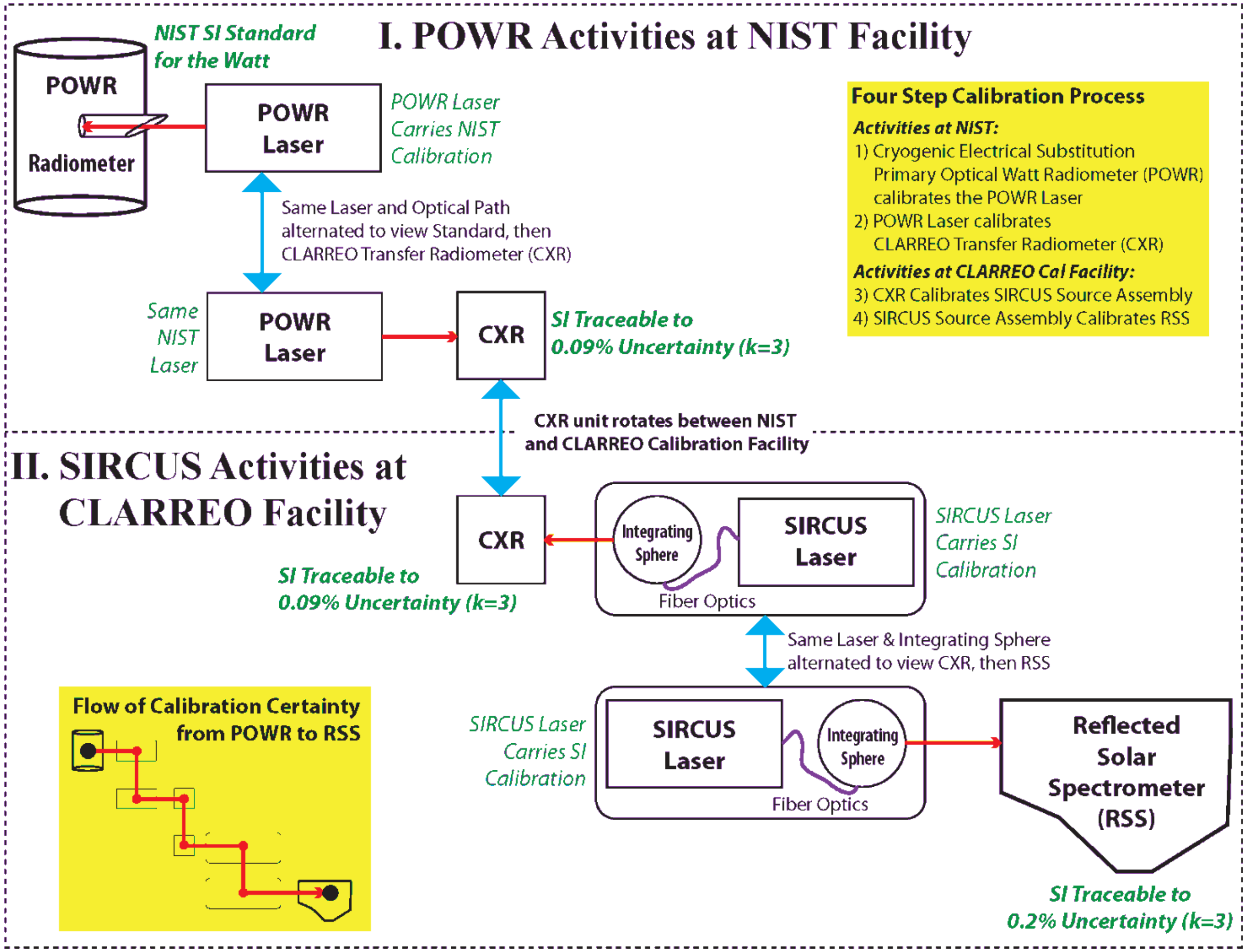


- Calibration approach is an integration of
  - Prelaunch characterization
  - Solar calibration
  - Lunar verification
- Physically-based sensor model provides the transfer to orbit



Prelaunch SI traceability accuracy

- NIST **currently** operates a system that can simulate on-orbit sources
- Monochromatic source to calibrate RSS to better than 0.2% absolute uncertainty (k=3)
- Output characterized by CLARREO Transfer Radiometer (CXR)
- Collaborating with NIST to develop technology for CLARREO (see backup charts for more information)
  - Develop CXRs for full spectral range
  - Ensure source available for CLARREO



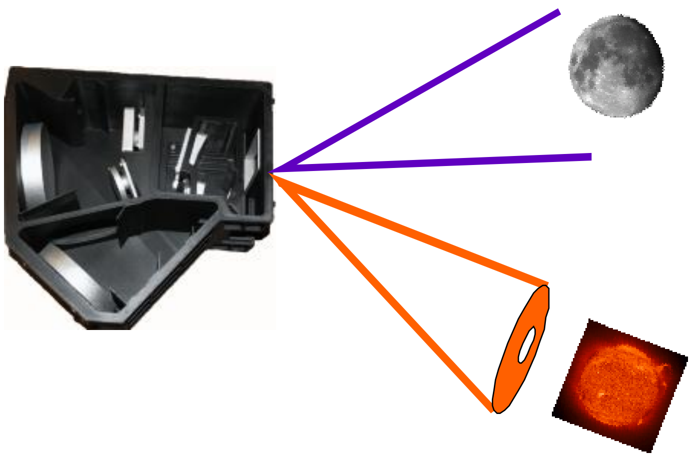
Accurate prelaunch calibration is first step to transfer to orbit

Technology development

- Efforts to improve accuracy rely on
  - Minimizing sensor complexity
  - Choosing appropriate approaches for SI traceability
  - Emphasizing calibration throughout sensor development lifecycle
- Low sensor complexity means no significant technology development is required (TRL 4 is lowest value)
- SI-traceability choices rely on laboratory-based calibrations already developed by NIST
  - Detector-based source calibration
  - Development of physically-based spectrometer models including well-understood error budgets
- Emphasis on calibration similar to methods developed for solar irradiance sensors (TSIS, TIM)
- Calibration effort still requires making NIST-based methods more operational

Technology Development

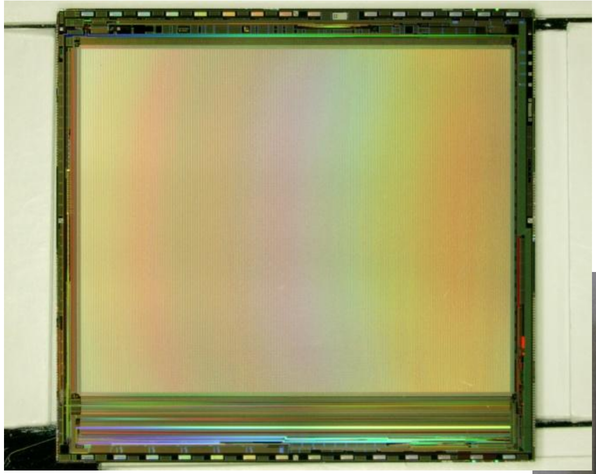
- Transfer-to-orbit error budget needs demonstration
- Calibration demonstrator provides tests of
  - Robust, portable tunable-laser facility including transfer radiometers with sufficient spectral coverage
  - Broadband stray light and polarization systems of sufficient fidelity
  - Depolarizer technology
  - Detector development especially for the red/NIR system
  - Thermal control of attenuators and detector needs to be proven
- Operating demonstrator in the field will provide check on instrument models
  - Sea level and mountain-top observations
  - Cross-comparisons with other systems
  - Solar views
  - Lunar views
  - Reflectance collects



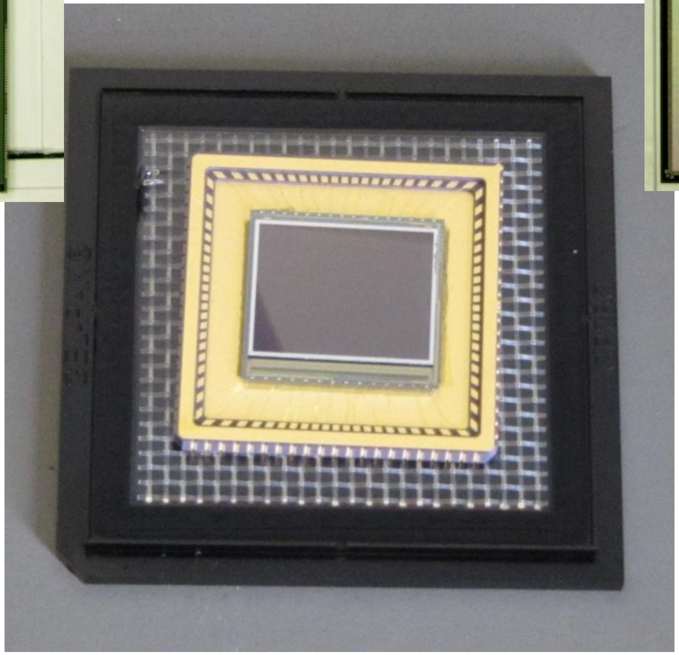
SOLARIS

- SOlar, Lunar for Absolute Reflectance Imaging Spectroradiometer (SOLARIS)
- Calibration demonstration system
- Develop and check calibration protocols and methods
  - Path to SI traceability (source and detector standards)
  - Ability to view sun and scene
    - Ratio of the solar irradiance and earth radiance for reflectance
    - Feasibility of attenuation methods: perforated plate, pinhole plate, neutral density filters
- Design and produce optics, with the optics in the Blue band (320-640 nm) being the most challenging
- Minimize polarization sensitivities
- Control/characterize stray light including multiple-order gratings
- Measure shortwave IR (600-1200nm) (Red) to demonstrate detector technology and validate thermal control stability

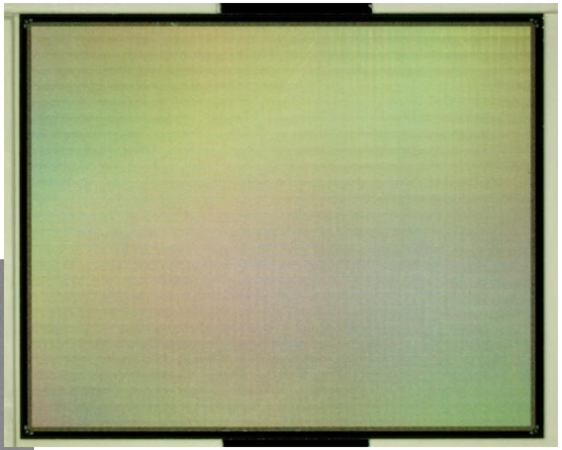
SOLARIS Silicon Detector



ROIC

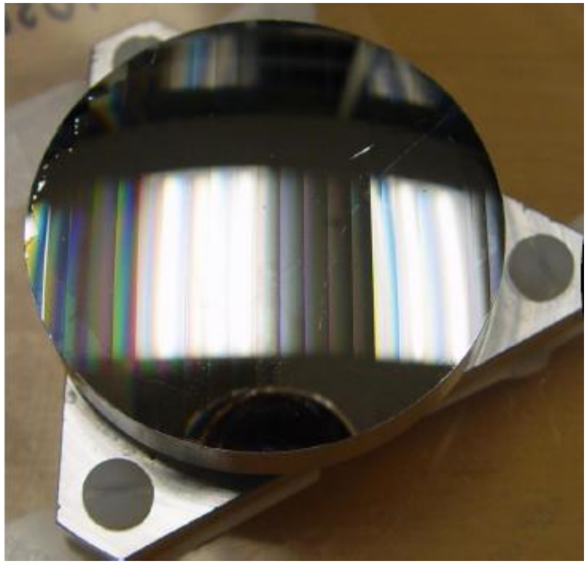


Detector Hybrid in a LCC carrier



Detector with In Bumps

Optic Components

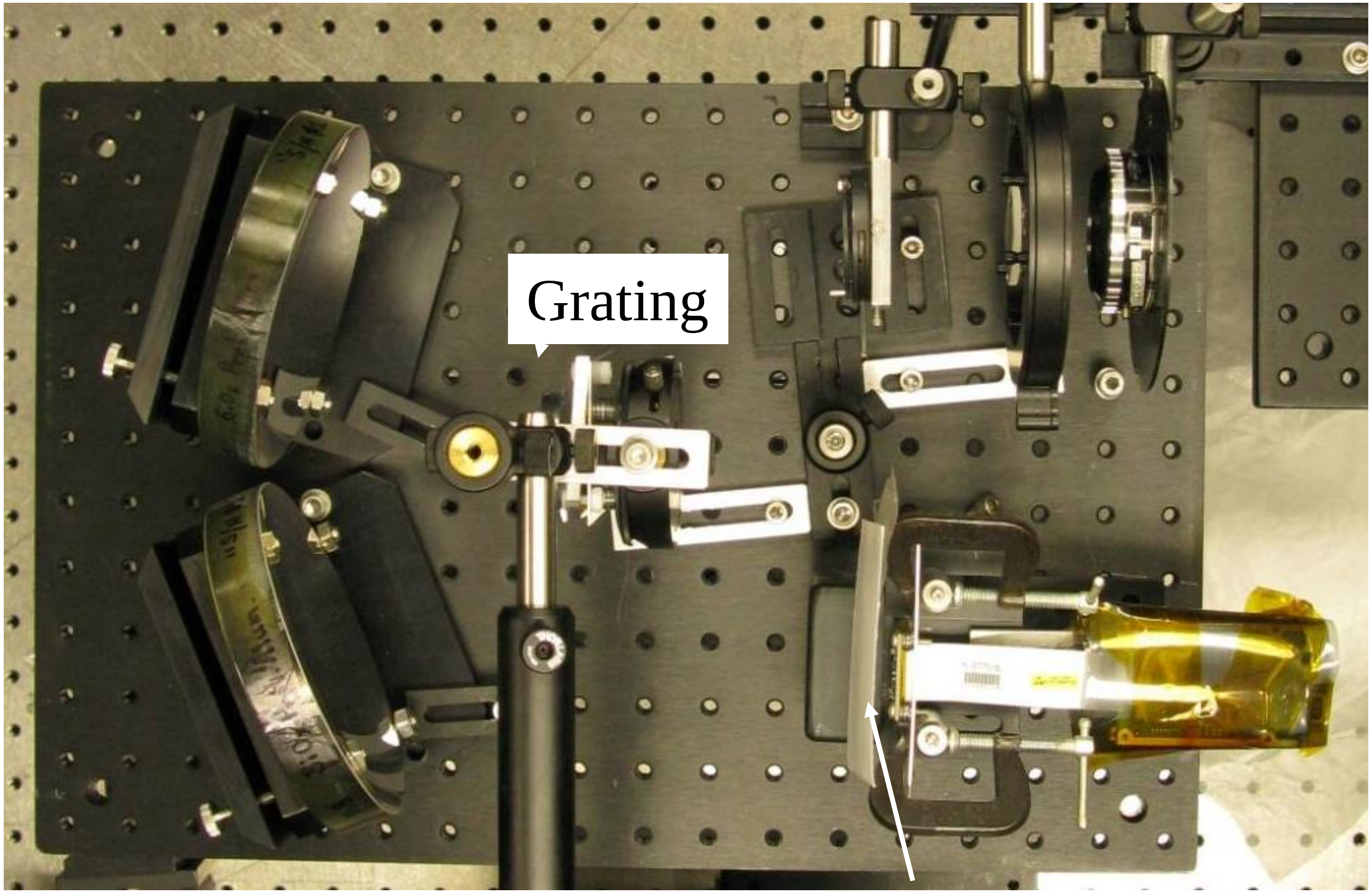


First unit grating replica

Optics set in shipping container

Grating Performance Measurements

TOP VIEW



SOLARIS Progress

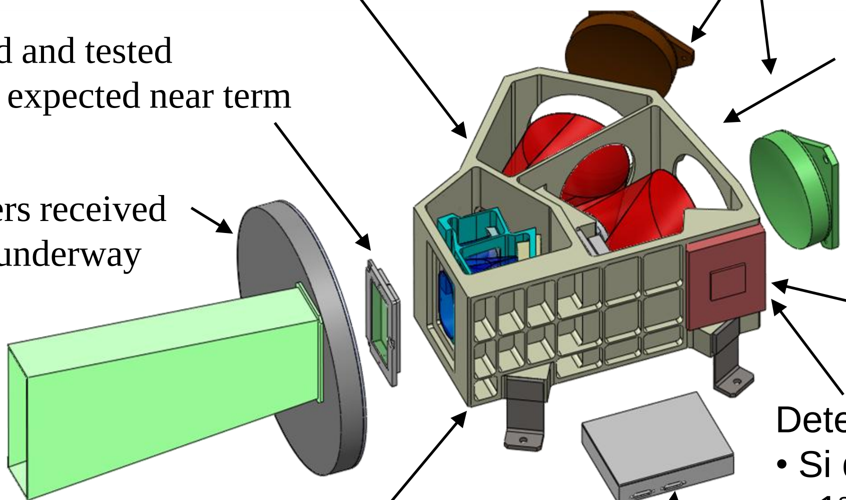
Slit
• Fabrication underway
• Silicon masks received

Optics
• Rough Machine Complete
• Diamond turn Figure and Polish at a Vendor underway

Depolarizer
• Blue Band received and tested
• Red Band delivery expected near term

Grating
• First unit received and being evaluated
• Additional replicas arriving
• Initial performance measurements look good

Attenuators
• Neutral Density Filters received
• Perforated Plate fab underway



Detector Housing
• Fabrication complete

Detector
• Si detectors nearly complete
  • 1st and 2nd units in characterization
• MCT detectors on contract
  • 1st unit due in May

Main Housing
• Fabrication underway

Lab and Test Equipment
• Test Lamps received
• Connectors received
• Clean facility preparation underway
• Characterization Components selected
• Vacuum and Purge equipment specified
• Thermal control equipment specified

Electronics
• Long lead parts purchase underway
• Task Plan submitted

Conclusions

- The Reflected Solar Spectrometer Concept met the science objectives
  - Design concept well within the current state of the art
  - Operations concept met the requirements for benchmark data, intercalibration of orbital assets, and on-orbit calibration/verification
  - There are adequate technical margins to cover future design changes.
- Calibration approaches still need demonstration
  - Demonstrator unit should begin testing in fall
  - Laboratory calibration protocols being developed

Backup Charts

Reflectance retrieval

- Equation below gives the baseline approach to reflectance retrieval as a ratio of earth-view data to solar-view data
- Terms are as defined

$$BRDF_{i,\lambda}^{earth} = \frac{S_{i,\lambda}^{earth}}{R_{i,\lambda}^{sensor} A_{sensor} \Omega_{sensor}} \frac{(T_{attenuator} A_{attenuator}) \langle R_{\lambda}^{sensor} \rangle}{\cos\theta_{solar} \sum_{k} \sum_{l} S_{k,l}^{solar} r_{k,\lambda}^{flat\ field}} \frac{a_{sensor}^{straylight}\, \omega_{sensor}^{straylight}\, a_{attenuator}^{straylight}}{r_{i,\lambda}^{flat\ field}\, r_{i,\lambda}^{nonlinearity}\, r_{i,\lambda}^{polarization}}$$

$BRDF_{i,\lambda}^{earth}$ *is the bidirectional reflectance distribution function for the i^{th} detector at wavelength λ*

$S_{i,\lambda}^{earth}$ *is the sensor output while viewing the earth*

$S_{k,l}^{solar}$ *is the sensor output while viewing the sun over each of k solar positions*

$R_{i,\lambda}^{sensor}$ *is the sensor response*

$\langle R_{\lambda}^{sensor} \rangle$ *is the average sensor response at a given wavelength*

$r_{k,\lambda}^{flat\ field}$ *is the flat field response relative to the average response*

A_{sensor} *is the area of sensor's collection area*

Ω_{sensor} *is the solid angle of sensor's collection field of view*

$T_{attenuator}$ *is the transmittance of the attenuator*

$A_{attenuator}$ *is the area of the attenuator's aperture*

$a_{sensor}^{straylight}$ *is the error factor due to stray light related to aperture area*

$\omega_{sensor}^{straylight}$ *is the error factor due to stray light related to field of view*

$a_{attenuator}^{straylight}$ *is the error factor due to stray light related to attenuator area*

$r_{i,\lambda}^{flat\ field}$ *is the error factor due to flat field*

$r_{i,\lambda}^{nonlinearity}$ *is the error factor due to detector non-linearity*

$r_{i,\lambda}^{polarization}$ *is the error factor due to polarization*

Driving equation for retrieval of reflectance

Calibration overview

- CLARREO reflectance retrieval relies on the ratio of the benchmark data to the solar data
  - Account for temporal variability in sensor
  - Can be converted to absolute radiance using a known solar irradiance
- Need to include uncertainties in sensor characterization
  - Straylight changing
    - Sensor solid angle (footprint)
    - Sensor aperture
    - Attenuator area
  - Detector response uncertainties
    - Nonlinearity
    - Polarization
    - Flat field correction

On-Orbit, Solar Calibration

- Solar calibration
  - Comparison with absolute solar irradiance
  - Temporal degradation of detectors and optics
  - Detector-to-detector changes
  - Evaluation of stray light
- Requires attenuating approaches

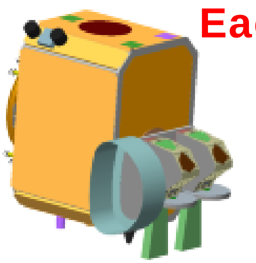
Prelaunch → **Post-launch**

Prelaunch

Absolute response $R^{sensor}_{i,j}$

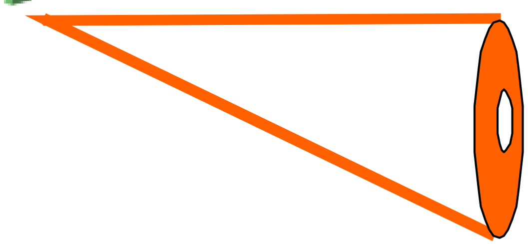
Relative response $r^{flat\ field}_{i,j}, \langle R^{sensor} \rangle$

Sensor Artifacts
$$\frac{a^{straylight}_{sensor} \ \omega^{straylight}_{sensor} \ a^{straylight}_{attenuator}}{r^{nonlinearity}_{i,j} \ r^{polarization}_{i,j}}$$



Each detector images full solar disk

$$R^{sensor}_{i,\lambda} = \frac{\sum_{x_{solar}} \sum_{y_{solar}} S^{solar}_{i,\lambda}(x'_{solar}, y'_{solar})}{(T_{attenuator} A_{attenuator}) E_{solar}}$$



Post-launch

Absolute response eval. $R^{sensor}_{i,j}$ *

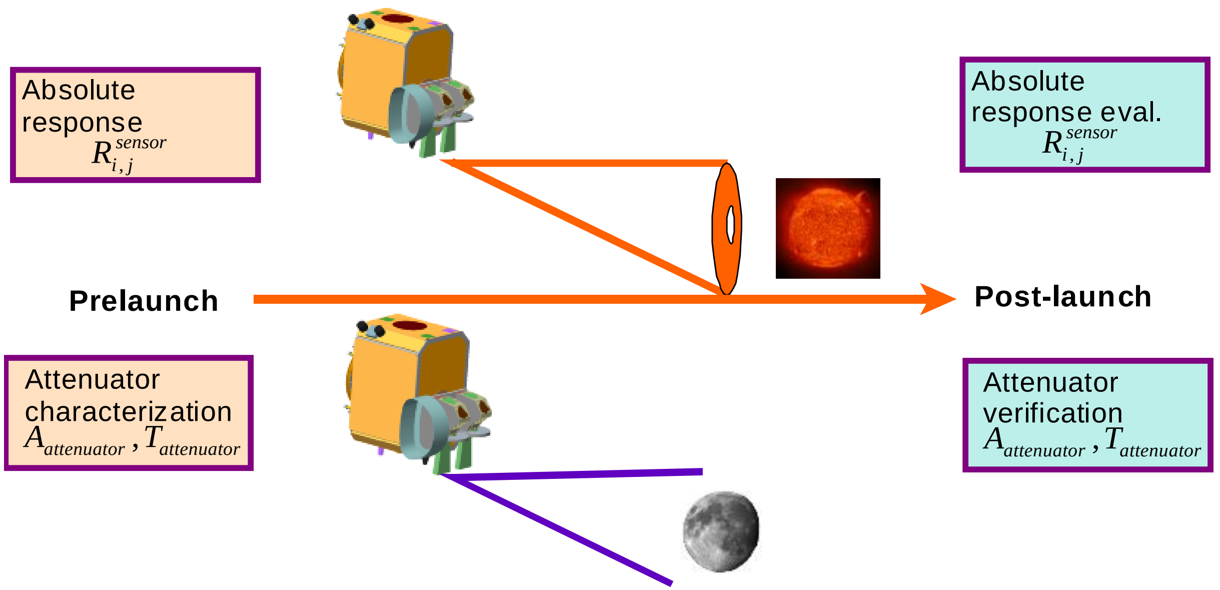
Relative response $r^{flat\ field}_{i,j}, \langle R^{sensor} \rangle$

Sensor Artifacts *
$$\frac{a^{straylight}_{sensor} \ \omega^{straylight}_{sensor} \ a^{straylight}_{attenuator}}{r^{nonlinearity}_{i,j} \ r^{polarization}_{i,j}}$$

Reflectance retrieval uses ratio of earth view to direct solar view

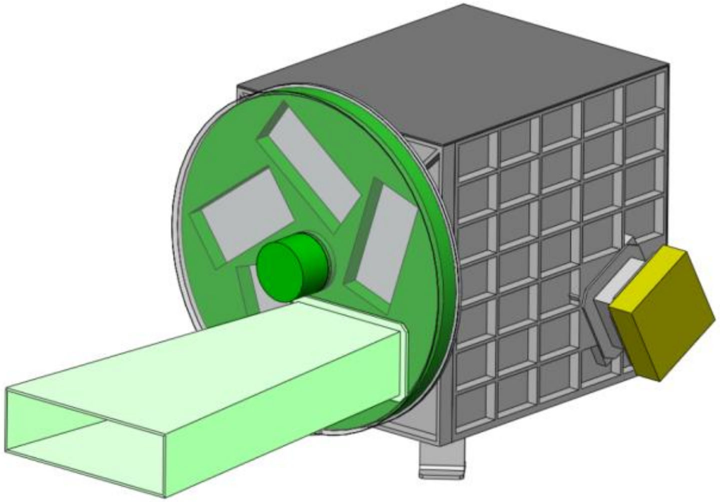
Attenuator verification

- Initial on-orbit view of sun as an absolute standard provides initial transfer to orbit
- Lunar views provide an invariant surface to assess the attenuator system
- View monthly at near-constant lunar phase to reduce variations
- Current accuracy of absolute lunar irradiance is not sufficient for CLARREO purposes
- Lunar views also provide information on stray light



Solar Calibration Mode

- Conversion to reflectance made via direct view of the sun
  - No onboard calibrator source is required
  - Requires attenuation of solar beam
- Solar calibration corrects for changes in solar output and instrument response
- Baseline design includes single attenuator wheel with 5 available positions
  - Dark current, safing and launch
  - Perforated Plate
  - Neutral Density Filter
  - Pinhole aperture
  - No attenuation

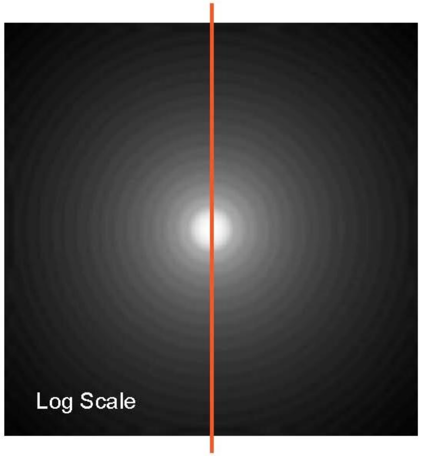


- Evaluating need for additional attenuators
  - Dual attenuator wheel assembly is feasible

Attenuators - Pinhole Aperture

- Single pinhole aperture can be used to reduce the incident solar energy to a value more similar to the earth-view energy
- Small-sized aperture leads to significant diffraction effects
  - Diffraction effects lead to spread of solar “image”
  - Spectrally-dependent effect
  - Small-sized aperture can also affect how the diffraction grating disperses the beam

Image of Sun at 2.4 μm using a 500 μm Pinhole



75 μm X 15 mm slit

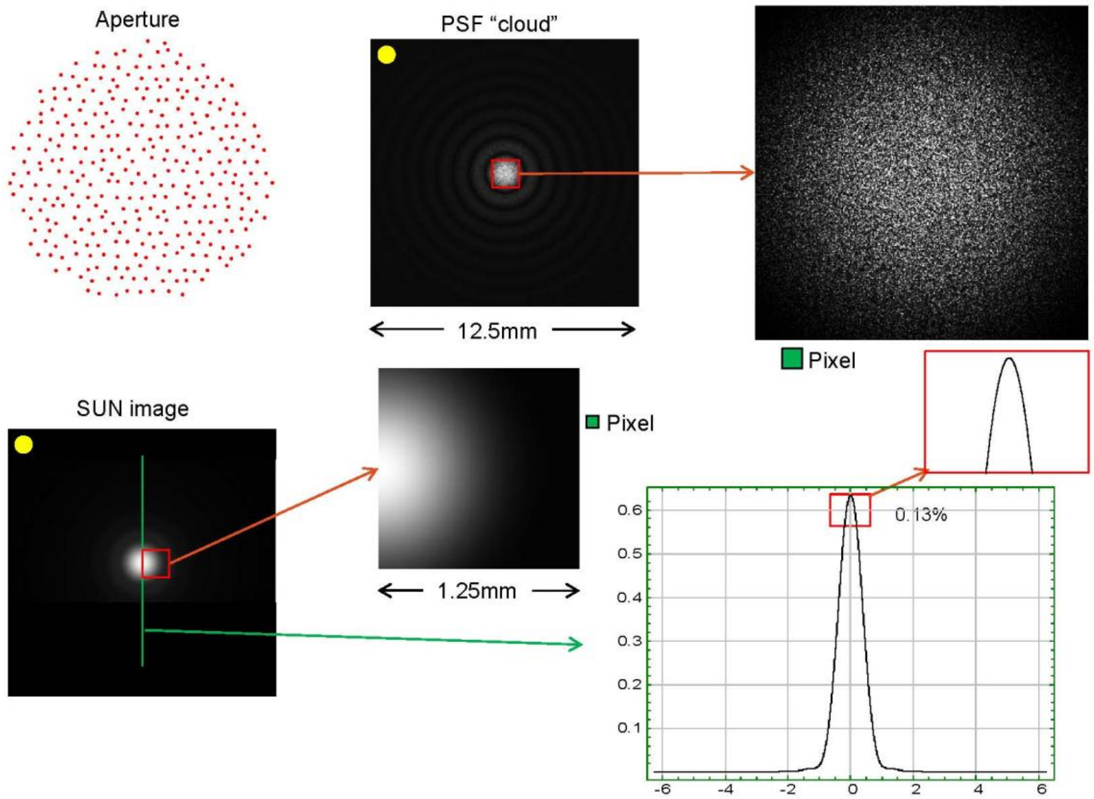
This example is for a disk of uniform brightness the apparent size of the.

Image of sun at 0.32 μm will be substantially sharper due to a narrower PSF in UV.

Attenuators - Perforated Plate

- Attenuates the radiance at the center of the solar image through blockage and diffraction
  - Attenuation up to a factor of 50,000
  - Produces a uniform beam across multiple detectors
- Avoids materials degradation problems
- Trade is on size and number of holes relative to attenuation and beam uniformity
- Strong spectral dependence

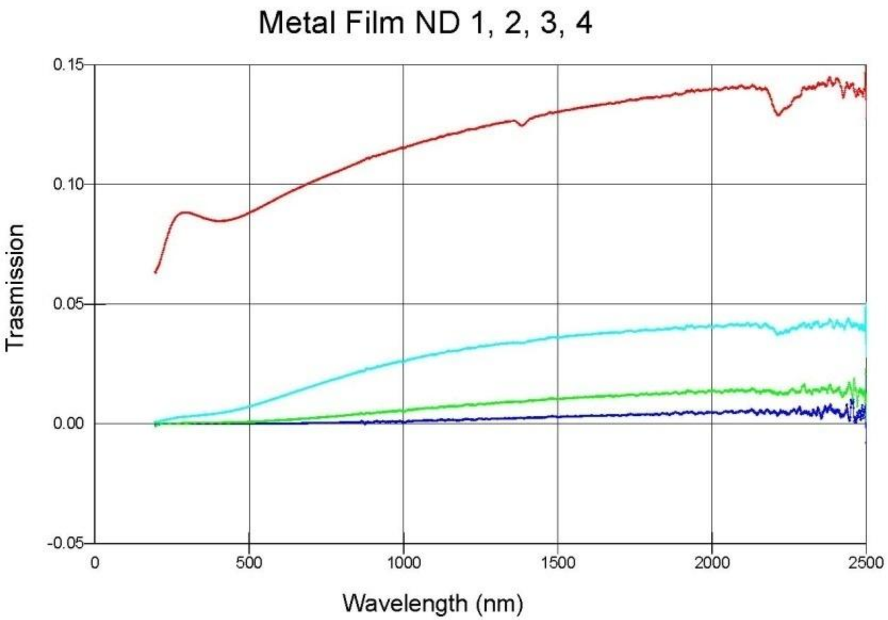
313 holes, random hex grid, random phase (0.6 μm)



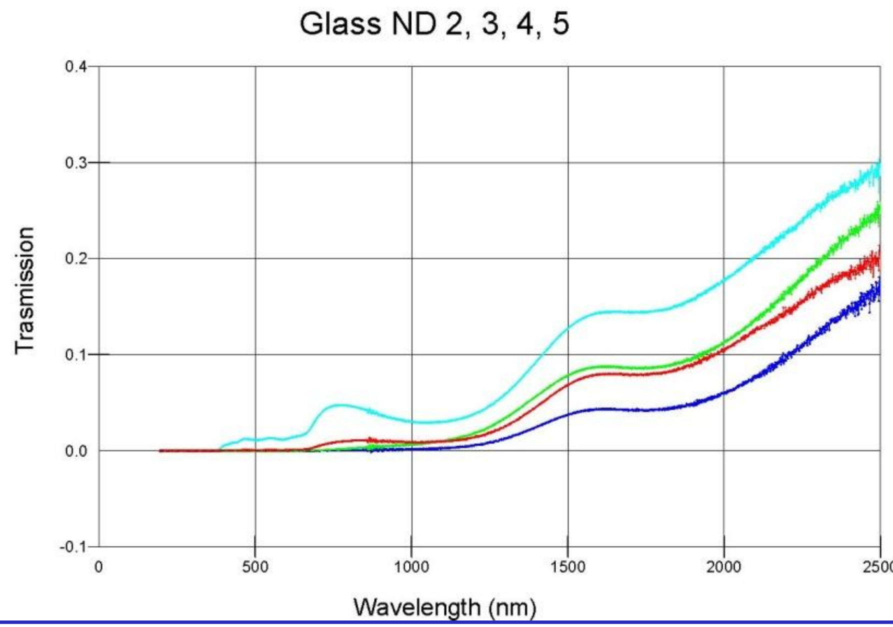
Attenuators - Neutral Density

- ND filters attenuate using either absorption or interference effects
- Spectrally-dependent
- Temporal degradation can be an issue
  - Pristine filter can be used
  - Requires additional slot in filter wheel

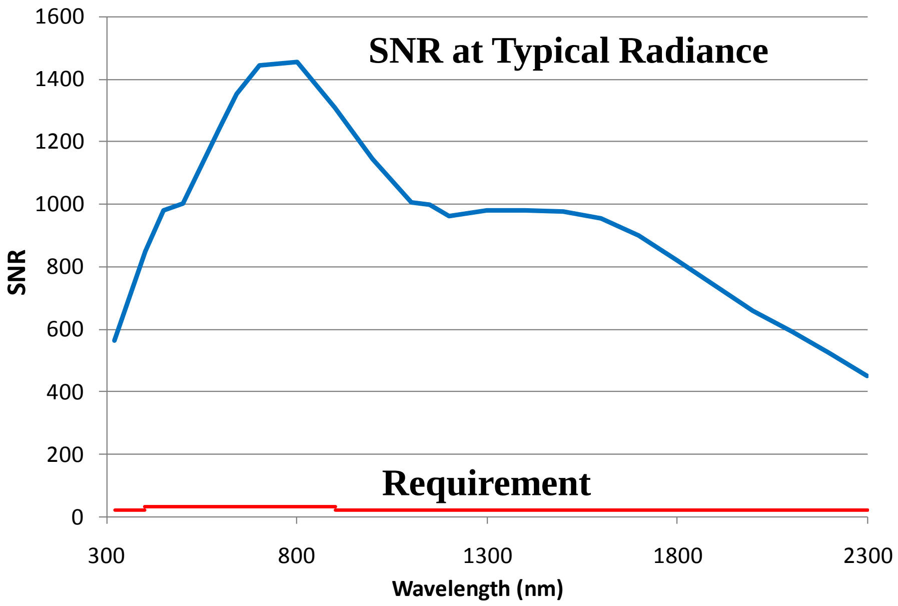
Melles Griot Metal Film on Fused Silica

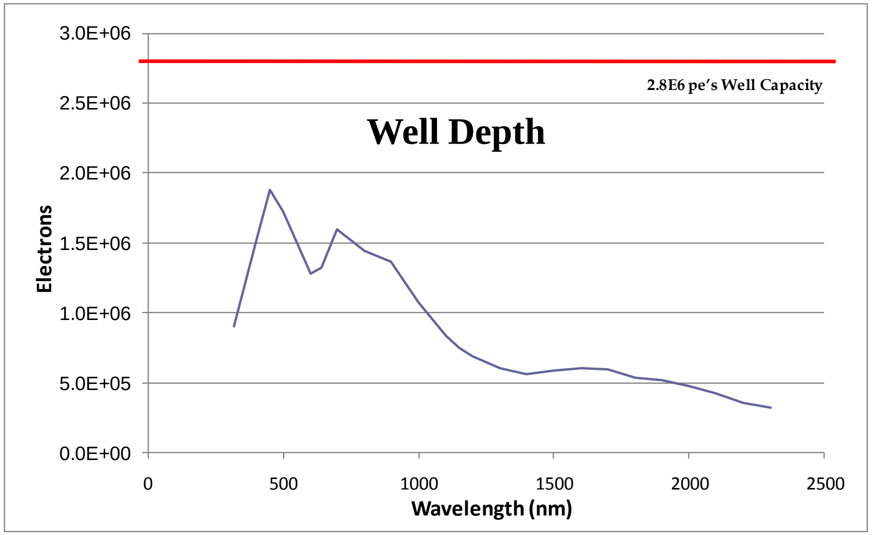


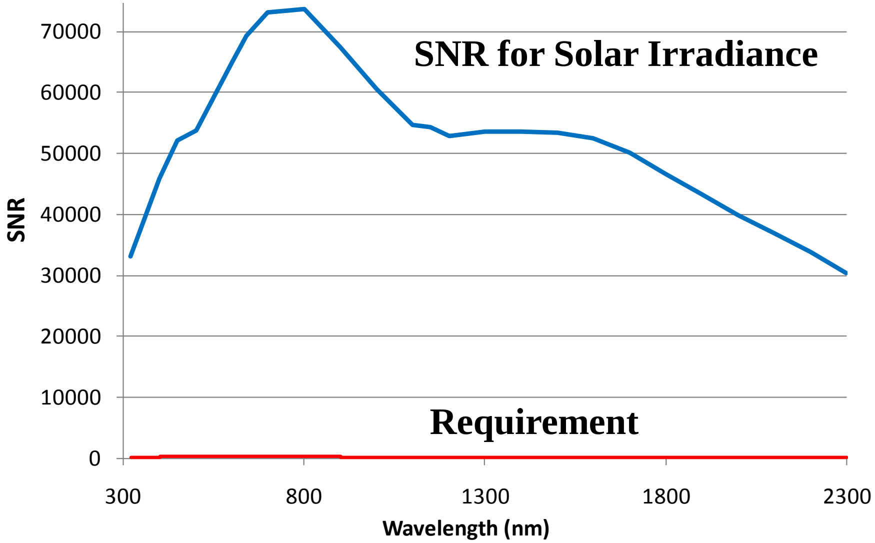
Melles Griot Glass Filters



Radiometric Performance Margin





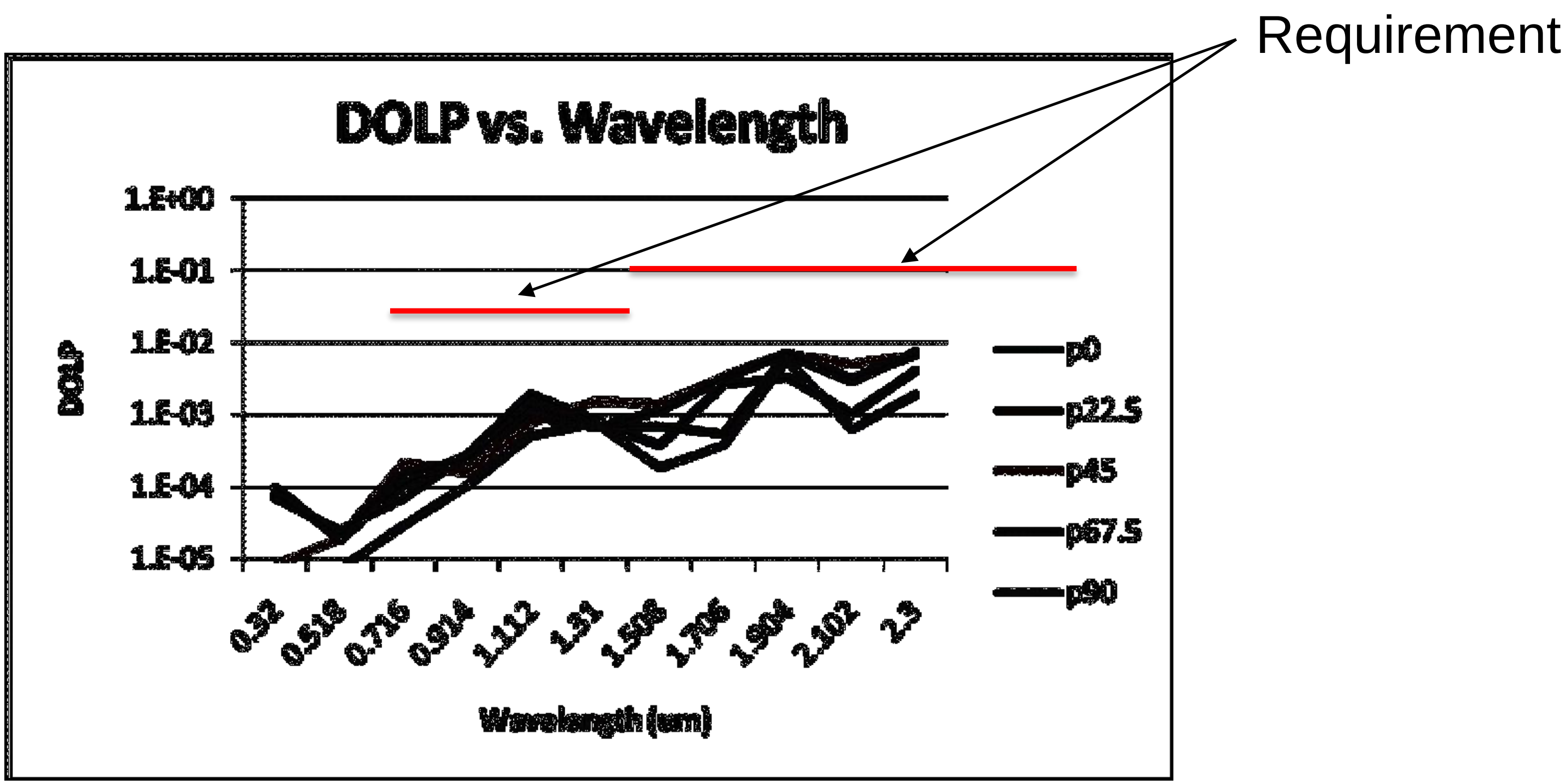


Expected radiometric performance far exceeds requirements while not exceeding detector well depth

Requirements Compliance

Polarization Sensitivity Compliance

Optical modeling of wedge depolarizers suitable for CLARREO meets the polarization requirement



Dual-Double Wedge Depolarizer with OA at 90°, Wedge angles clocked at 45 °

Calibration Flow